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Review

Addressing the Urban Heat Islands Effect: A Cross-Country Assessment of the Role of Green Infrastructure

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Abstract: The Urban Heat Islands (UHI) effect is a microclimatic phenomenon that especially affects urban areas. It is associated with significant temperature increases in the local microclimate, and may amplify heat waves. Due to their intensity, UHI causes not only thermal discomfort, but also reductions in the levels of life quality. This paper reviews the important role of green infrastructure as a means through which the intensity of UHI may be reduced, along with their negative impact on human comfort and wellbeing. Apart from a comprehensive review of the available literature, the paper reports on an analysis of case studies in a set of 14 cities in 13 countries representing various geographical regions and climate zones. The results obtained suggest that whereas UHI is a common phenomenon, green infrastructure in urban areas may under some conditions ameliorate their impacts. In addition, the study revealed that the scope and impacts of UHI are not uniform: depending on peculiarities of urban morphologies, they pose different challenges linked to the microclimate peculiar to each city. The implications of this paper are threefold. Firstly, it reiterates the complex interrelations of UHIs, heat waves and climate change. Secondly, it outlines the fact that keeping and increasing urban green resources leads to additional various benefits that may directly or indirectly reduce the impacts of UHI. Finally, the paper reiterates the need for city planners to pay more attention to possible UHI effects when initiating new building projects or when adjusting current ones.

Keywords: climate change; cities; urban heat islands; resilience; green areas

1. Introduction

Cities continue to be the basic unit of economic development, symbolizing an engine for change and transformation [1]. Compared to rural areas, they play an essential role in terms of economic development, as they offer greater opportunities for education, employment and prosperity. At the same time, urbanization as a trend has enormous environmental consequences, both global and local. On a local level, the negative impacts of urban expansion relate, for example, to traffic congestion, informal settlements, urban sprawl, environmental pollution and an overexploitation of water resources. Globally, urbanization-related emissions resemble a significant contribution to climate change. For instance, according to a recent study by [2], the residents of just 100 cities account for 20% of the global carbon footprint [3,4].

Changes in urban form are assumed to be closely related to these negative impacts and to some extent may drive them [5–9]. In 2016, the global average population density was 378 pop/km², and was doubling in comparison with 1961 [10]. The same year, 54.5% of the people were living in urban contexts [11], an increase of 24.5% compared to 1950 [12]. By 2050, 68% of the world's population is projected to be urban [13]. Three countries alone—India, China, and Nigeria—are expected to account for 35% of the growth in the world's urban population between 2018 and 2050 [13]. As more and more people keep moving to urban areas, the current trend towards urbanization continues to persist, and with it, the aforementioned environmental consequences.

Climate change and its already observable impacts on urban areas, such as longer, more severe and more frequent heat waves, are becoming a key field of study [14]. The UHI effect resembles an additional hot anomaly, and the resulting heat stress in urban areas is often found to be even higher, indicating synergies between UHI and elevated temperatures in urban and suburban areas and heat waves [15–18].

The interaction of rising temperatures due to climate change, heat waves and elevated temperatures in urban and suburban areas is projected to result in increasingly harmful impacts, e.g., on human health, and to negatively influence air quality and water availability [17,19]. On the other hand, cooling strategies, such as urban greening, that are developed to tackle locally elevated temperatures could assist urban residents in adapting to climate change-related impacts and, at the same time, lower greenhouse gas emissions that lead to climate change [20]. Besides global temperature rise, heat waves are projected to become more frequent [21,22]. Based on data from Germany's National Meteorological Service (DWD), Figure 1 illustrates an increased occurrence of heat waves in Central Europe between 1952 and 2015. In the summer of 2018, heat waves in the Northern hemisphere reached unprecedented levels in some regions [23]. From a global health perspective, the 2019 Lancet countdown report [24] recorded a record number of additional exposures to heat waves, totaling 220 million people in 2018. It also projects that vulnerability to heat extremes will continue to rise in every region of the world. Heat stress not only affects the physical wellbeing in general, it also impacts the ability of the workforce: in 2018, 45 billion additional working hours are reported to have been lost i.e., worker productivity has been reduced due to rising temperatures, when compared to the year 2000 [24].

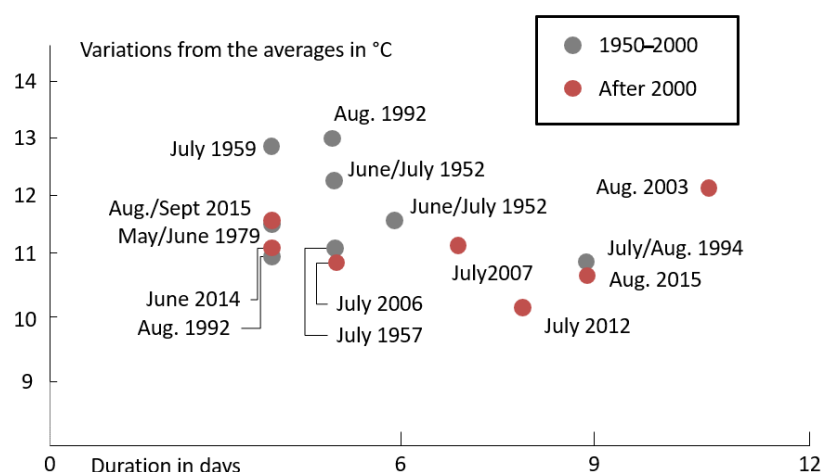


Figure 1. Occurrence of heat waves in Central Europe (modified from [25,26]).

Regarding cities, the impacts of climate change on urban areas are likely to worsen. Ref. [27] refer to a projected increase of weather and climate-related disasters both in number and severity. Several human-induced stresses, such as surface sealing or heat-absorbent surface covers, are contributing to the problem.

In the light of these challenges, a question that may be asked is: how can one ensure the well-being of urban residents, while at the same time tackling dangerous climate change and avoiding lasting damage to vital ecosystems? Environmentally sustainable solutions using the adaptive and mitigative qualities of green infrastructure have been identified at the local level. For example, [28] suggest increased urban vegetation cover as one effective way to mitigate elevated temperatures in urban and suburban areas, and [29] observed the cooling effect of green infrastructure in Harbin, China. Comprehensive solutions would need to go hand-in-hand with further sustainable development goals such as reducing poverty, improving quality of life and promoting sustainable economic development. A ‘green agenda’ may thus be a vital part of a holistic, city-led strategy towards improved economic, social and environmental sustainability.

It is against this background that this paper reports on an effort to better understand how the phenomenon of an urban heat island affects a set of cities, and examines a way to cope with it, linking it with the possible adaptation potential of green infrastructures.

2. Urban Heat Islands: Definition, Facts and Trends

By definition, an urban heat island (UHI), a micro-climatic phenomenon that varies with city size, refers to elevated air temperature differences in urban and suburban areas compared with rural surroundings, [30,31]. Urban heat islands need to be distinguished into two types:

- Surface UHIs are typically present day and night but strongest during the day and typically largest in summer, with up to 12 °C differences in daily urban versus rural surface temperatures [32].
- Atmospheric UHIs, typically observed during predawn and night during the winter time, are further distinguished into the canopy layer UHI, i.e., the layer of air where people live from ground to roof/tree tops, and the boundary layer UHI from roof top level to about a height of 1.5 km, with a temperature range between 7–12 °C [32].

The canopy UHI is the most commonly observed type, and thus often referred to in urban heat island studies [32]. Surface UHIs show more temporal and spatial variation than the atmospheric kind. Whereas the first type of UHI is most intense during the day and during summertime, the atmospheric kind is most intense during predawn and night and in the winter, [32]. Paolini [33] observed that the typical increase in daily surface temperature may be more strongly associated with urban expansion processes, whereas the rise in nightly temperature may more strongly relate to urban densification processes.

As far as causes of the phenomena are concerned, rapid urbanization and the corresponding density of buildings, which have changed the land surface in cities and transformed the urban environment, are acknowledged to be among them [32,34,35].

The most frequent causing factors of urban heat islands involve reductions in evapotranspiration and convection and increases in heat storage, net radiation and anthropogenic heat, all of which are mostly correlated to diminished vegetation, the widespread use of impermeable surfaces, certain urban materials (thermal diffusivity and reflectance features), urban geometries (barriers to relieve heat and slowing winds), air pollution and energy use [36,37].

The intensity of the UHI effect is influenced by a range of urban proxies, e.g., urban morphology [38], along with meteorological conditions [39], seasons [40] and the time of the day [17]. For example, the UHI effect is usually developed during high pressure (anticyclone) weather situations with clear skies and calm air nights, as a result of the delayed cooling of the city's artificial surfaces and buildings compared to surrounding natural areas [37], but also within the urban area temperature differences that occur due to differences in land-use and surface characteristics [41]. Peng et al. [28] showed in their study of more than 400 large cities that the average annual UHI intensity during the day is higher than at night. As size typically has the greatest influence on UHI intensity [42], most research has focused on large cities, even though Oke [43] and Park [44] showed early on that even smaller towns (settlements) with a population of only 1000 inhabitants in North America, Europe, Japan, and Korea can also show a heat island effect. However, there still appears to be a research gap concerning UHI patterns of mid- and small-sized cities.

Strong nocturnal UHI intensity may appear during the early night [41,45,46], for example, as observed in the Hungarian case study of Szeged, a city of about 165,000 inhabitants: the mean annual UHI effect became observable immediately after sunset, reaching its maximum about 3 h later and lasting a maximum of 9 h [47]. These air-temperature-based atmospheric UHI intensities are higher and positive during the nighttime but lower and negative during the daytime, whereas surface-temperature based UHIs that are investigated through satellite data were positive during both day and night [48,49]. Based on data from the second part of the 20th century and the first decade of the 21st century, Tzavali et al., [50] and Leal Filho et al., [51] summarized UHI findings from North America, Asia, Europe, Africa and Australia.

As urban heat islands produce significant changes in the local microclimate, the intensity of the UHI has manifold consequences at the local level [51], which can be clustered under different aspects, as seen in Figure 2.

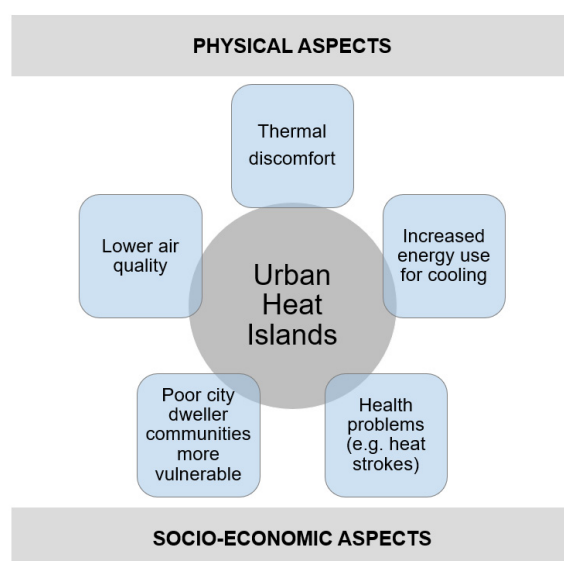


Figure 2. Some of the aspects and impacts of UHI.

Negative impacts mostly occur during summer periods as a result of a higher number of tropical nights and the corresponding additional demand for cooling energy in residential houses and offices. For example, results based on three years (2014–2017) of air temperature monitoring from Novi Sad (Serbia), a European mid-sized city, recorded 35 to 39 tropical nights in densely built-up areas, compared to four such nights in the hinterland [52]. The latest evidence from the global health community shows that elevated temperatures substantially decrease workforce productivity [24]. Correspondingly, a decrease of social and economic urban activity as well as an increase in energy consumption needs to be anticipated for proper planning [53]. UHI can also contribute to a higher intensity of heat waves in urban areas that may lead to outdoor and indoor human thermal discomfort and health problems of the population, i.e., higher morbidity, exhaustion, dehydration and mortality cases [54]. During such heat waves, dwellers in urban areas may experience sustained thermal stress both day and night, whereas inhabitants of rural environments often obtain relief from thermal stress at night [55]. However, UHI may also have positive effects in colder climate areas and during winter periods through extended frost- and ice-free periods, a reduced period of snow cover, longer crop growing season and reduced energy demand for heating [55,56], among others.

Many urban climatology studies on the existence, distribution, complexity and effects of UHI in cities around the world have been published, and studies have been performed in most of the bigger cities (see, for example, Peng et al.'s [28] assessment of 419 big cities). However, UHI magnitudes need always be viewed with caution. Indeed, Stewart's [57] systematic review criticized a substantial share of the UHI literature as scientifically indefensible, because the scrutiny of findings and rigorous documentation of primary research were two necessary requirements for good practice and credible results. Moreover, even though UHIs represent a well-known problem of cities, the data collection for the complex assessments remains challenging, and interdisciplinary approaches are increasingly pursued, combining insights from climate, environmental and social sciences to address such multidimensional phenomena. For example, Gartland [36] explored how microclimate and heat stress may influence social vulnerability, whereas Wilhelmi and Hayden [58] explored urban vulnerability to extreme heat. Huang and Cadenasso [59] assessed links between neighborhood social conditions, land cover and surface temperatures. Depietri et al. [60] identified links to ecosystem services in their social vulnerability analysis of an urban area and its vulnerability to heat waves.

However, despite the many studies performed to date, it is evident that the accuracy of determining the UHI effect is of vital importance for urban areas as they attempt to both mitigate climate change and improve their sustainable urban development without compromising the wellbeing of their inhabitants [50].

3. The Potential of Green Infrastructure for Urban Adaptation

Over the last decades, an increase of UHIs could be observed as a manifestation of micro-climatic changes in urban environments seen in cities worldwide. Temperature measurements suggest an increasing trend in both urban and hinterland areas that may be strongly related to urbanization and vegetation [14,50,51,61,62]. If cities seek to become more resilient to both long-term impacts of climate change and short-term UHI effects, it is essential to improve adaptation efforts by sustainably modifying the city structure, the building design, and the urban planning of living space [63,64].

A robust integrated approach involving urban planners, architects, meteorologists, climatologists, geographers, economists and social scientists appears to be useful when developing UHI adaptation strategies. Zhou et al., [42] suggested changes in urban form, avoiding large, compact or rotund cities. Masson et al. [63] presented a systemic modeling approach that combines prospective scenarios and spatially explicit models, providing interactions between climate change, city structures and the urban economies. Leal Filho et al. [51] published a review of tools for urban planners when mitigating and adapting to the UHI phenomenon.

Urban green space in cities may be regarded as an essential countermeasure against urban heat islands [19,65,66], and expert studies argue that more actions should be taken to increase the share of green areas in cities for mitigative and adaptive purposes [35,67,68]. For the purposes of this paper, green-infrastructure refers to bio-based infrastructure only. For instance, plants provide shade and thermal insulation [69], and they help to regulate noise and air pollution [70].

During moderate winds, intra-urban green areas (parks) have the effect of decreasing air temperature not only inside the green area, as illustrated by Feyisa et al. [71] for Addis Abbeba, but also from a few hundred meters to a few kilometers distant, depending on park size [72]. Stanganelli and Gerundo [73] developed guidelines for densely built areas, showing how natural cooling in urban areas can be improved through a smart configuration and distribution of green areas. Thus, strategies for providing cooling effects in the urban environment, such as planned green and blue areas, may be helpful and have been deployed to mitigate UHI effects [55,56,70,74–76]. For example, focusing on spatial-temporal changes of land cover and surface UHI effects in the Pearl River Delta in China, Wang et al., [77] analyzed the spatial pattern of an increase in land surface temperatures (LST) under the influence of a comprehensive land cover change, i.e., in particular the densification and vertical enhancement of existing buildings. Interestingly, in a study of the Baltimore (USA) neighborhood that focused on an assessment of social conditions, land cover and land surface temperatures (LST), Huang and Cadenasso [59] observed that land cover was not the characteristic feature of the spatial variation in surface temperatures, but rather the neighborhood's social conditions. Further findings pointed towards a key influence of land cover as 'the driving force, leading both neighborhood social conditions and LST to vary across space' [59]. This is in line with Giseke [78] who argued that open space in a thinned-out city provides two advantages: it may contribute to more green areas in cities while maintaining a socio-spatial continuum, and it allows the city planners to exploit potential transformation processes, i.e., by creating a new urban leisure culture that expands the traditional repertoire of urban open spaces. This could be in the form of recreational activities to ensure continual use, which engenders the involvement of communities in the routine maintenance of the public open spaces [79].

In agreement with findings from Adedeji and Fadamiro [79] and Yiannakou and Salata [80], it can be asserted that one of the best planning tools for both adaptation to and mitigation of urban climate change is Green Infrastructure (GI), which is an ecosystem-based approach. GI essentially refers to a multifunctional network of environmental assets. These assets are public and private, existing and new, and cover all spatial scales. The design and management of this network may both contribute to the sustainability of communities and enhance the local character of urban areas [81]. The following assets may be attributed to a city's Green Infrastructure network [82,83]:

- Public parks and gardens, including urban parks, open space reserves, cemeteries and formal gardens
- Greenways, including river and creek corridors, cycle ways and routes along significant transport (road, rail and tram) corridors
- Residential and other streets, comprising street verges and associated open space pockets
- Sports and recreational facilities, including tracks, golf courses, school and other institutional playing fields, and other significant parks
- Private/semi-private gardens, including shared (communal) spaces around apartment buildings, backyards, balconies, roof gardens and community (productive) gardens
- Green roofs and walls, including roof gardens and living walls
- Squares and plazas, including both public and private courtyards and forecourts
- Natural green space, including national parks and nature reserves, wetlands and coastal margins
- Utility areas, including quarries, airports, and large institutional and manufacturing sites. This category also includes unused land reserved for future use

- Agricultural and other productive lands, including vineyards, market gardens, orchards and farms

Green infrastructure, or resources, can thus perform multiple roles in urban areas, such as providing recreation, biodiversity (especially biodiversity conservation planning), cultural identity, environmental quality and biological solutions to technical problems [84]. Green resources can also be seen as comprising all of the natural, semi-natural and artificial networks of multifunctional ecological systems within, around and between urban areas, at all spatial scales [84,85]. Importantly, green resources can deliver multiple benefits from the valuable urban space it occupies, compared with traditional single-purpose engineering infrastructure [86]. It is this multifunctionality of green resources that differentiate it from its 'grey' counterparts, which tend to be designed to perform one function, such as transport or drainage, without contributing to the broader environmental, social and economic context [87]. Hansen and Pauleit [88] developed a conceptual framework that may be used to examine this multifunctionality to gather results that may support the mainstreaming of green infrastructure in urban planning.

Green resources do not only support adaptation, but also mitigation efforts. Human-related activities (building, power and heat production, transportation) in cities are responsible for about 70% of the CO₂ emissions; therefore, climate change mitigation requires rapid modification of a city's metabolism [89–91]. Although the achievements of emission reduction goals are mainly related to a modification of production and consumption patterns and increases in efficiency [89], the cooling effect of urban green resources may indirectly translate into lower CO₂ emissions by decreasing the power demand for indoor cooling and heating [92–95]. At the same time, it can increase carbon storage and sequestration rates [96–98]. Green approaches may also contribute to reducing transport-related emissions by linking strategies to reduce or avoid private car usage with cycling and pedestrian facilities (i.e., green corridors, parks). This may reduce pollutants as well [99].

However, perhaps the most crucial contribution of urban green resources from a climate change perspective is that they foster the resilience building of urban dwellers. Due to the UHI effect, urban dwellers are particularly vulnerable to thermal stress and their impacts that are being intensified due to climate change [64]. For urban areas to be sustainably livable both now and in the future, as well for ensuring the filtration of pollution, noise reduction and thermal comfort, there appears to be a solid case for the implementation of urban greening policies and strategies, especially in the developing countries of the global south.

4. Methodology

Based on the need for more international research in order to foster a better understanding of the UHI effect and corresponding adaptive measures, a study was performed in the course of 2018–2019. The methodology adopted is based on an analysis of case studies of 14 cities in 13 countries. This makes it one of the most comprehensive studies on UHI performed to date. Operationally, the authors initially collected evidence of the existence of UHIs, based on available literature sources in the sampled areas (see Table 1).

As a second step, the Köppen-Geiger classification scheme was used to indicate the respective climate zone (i.e., tropical, temperate and continental) and its distinctive temperature and precipitation regime that influences the micro-climate in the studied cities, in order to highlight the differing climatic conditions in cities that their inhabitants are exposed to and which need to be considered for future climate-smart city planning and development.

The exploratory case studies are based on an in-depth analysis of published journal articles and relevant secondary sources. In parallel, the authors identified city districts that are currently affected by the UHI effect (e.g., urban sites in city centers which are more prone to UHI) and other areas—such as parks and urban woodlands—which are less so. These serve the purpose of illustrating the potential influence of green areas on

the intensity of the UHI in each sampled city, hence assisting the 14 cities to obtain a better understanding and cope with the multiple challenges posed by the UHI effect.

Table 1. References on urban heat islands in investigated city sample.

City/Country	Literature Source:
Beijing/China	[100,101]
Belgrade/Serbia	[34]
Buenos Aires/Argentina	[102,103]
Dhaka/Bangladesh	[104,105]
Lagos/Nigerai	[106,107]
Hamburg/Germany	[108,109]
Kuala Lumpur/Malaysia	[77,110]
Montevideo/Uruguay	[111]
New Delhi/India	[112,113]
Novi Sad/Serbia	[114,115]
Rio de Janeiro/Brasil	[116,117]
Seoul/Korea	[117,118]
Sydney/Australia	[119,120]
Warsaw/Poland	[121]

A limitation of this study is that official data sets on green areas differ substantially in their measurement approaches, i.e., often disregarding certain parts of a city's vegetation or varying in definition of what exactly is considered a green area. However, for making informed decisions on how to deal with the UHI effect, virtually all green areas of a city, including their distinctive spatial distribution, would need to be taken into consideration. For example, Hamburg's officially communicated figure results from including forests, recreation and green spaces (16.7%), nature protection areas (8.4%), additional protected spaces (19%), but also includes farming, fruit growing and horticulture areas (25%)—with the latter not being reflected in green area indications of other cities, rendering comparisons nearly impossible. To increase the meaningfulness of this study, the current research gave emphasis to recent information sources. The limitations of the study are outweighed by the fact that it is one of the most comprehensive reviews undertaken on the nexus UHI-green areas, investigating a set of cities whose total population is in excess of 40 million people.

5. Results and Discussion

According to the Koeppen-Geier classification, the assessed cities can be associated with three of the five major climate zones (A—tropical climate, C—temperate, D—continental). Allocating the cities further to the respective subcategories allows for a finer characterization of the typical micro-climatic environments. Four of the investigated cities (Kuala Lumpur, Dhaka, Lagos, Rio de Janeiro) show a tropical (megathermal) climate, six cities are located in a temperate mesothermal climate zone and three cities (Hamburg, Warsaw and Beijing) are associated with the continental climate zone. Figure 3 illustrates the city locations and their climate zones in a global map.

Based on the need to provide a better understanding of UHI and sustainable countermeasures such as green areas, this study, performed across 14 cities in 13 countries, provides an integrated overview of cities in developed and developing countries that face urban heat island effects on their territories. Table 2 provides an overview of the assessed cities that suffer from UHI effects and highlights the results of the empirical analysis. The developed data collection matrix consists of a set of indicators that together offer a consolidated overview of key characteristics of the assessed cities that provides key information on UHI parameters, e.g., city size, which has been found to have the strongest influence on UHI intensity [42], main urban districts affected by the UHI effect and examples of larger green areas (parks).

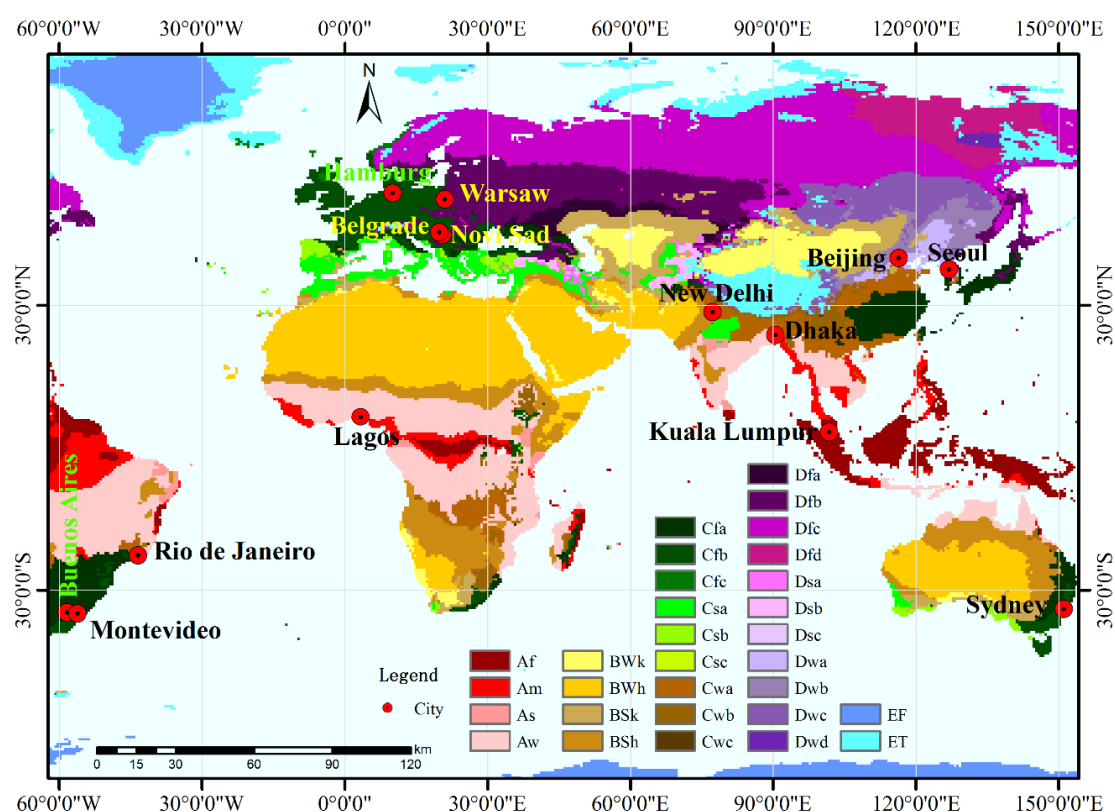


Figure 3. Geographical location of investigated cities and corresponding climate zone (Koeppen-Geiger classification). Source: Authors' own compilation.

Table 2 comprises two different kinds of UHI-related parameters as described in Leal Filho et al. [51], i.e., linked to geographical location (Koeppen-Geiger climate classification) and to urban environment (city size, population density). In particular, the analysis highlights specific city areas affected by the UHI effect and couples this with information on the total share of green spaces existing in the cities and specific examples.

The results outlined in Table 2 illustrate the fact that Belgrade, with less than 2% of the total urban space dedicated as green areas, is especially vulnerable to UHI. The limited amount of green areas means that retention of urban heat is likely to be more intensive, a trend also seen in Lagos, Nigeria where it does not exceed 5%.

In addition, regions where UHI—especially in the summer months—is known to be a problem, such as in Greater Sydney, Australia, can count on the fact that 46% of the area is supported by green infrastructure. This suggests that it is in a better position to cope with the problem than Seoul, South Korea, where total green areas are a lot smaller.

From the sampled cities, Beijing (China), Sydney and Hamburg (Germany) have the highest proportion of green areas. Due to their geographical positions however, UHI is more of a problem in Beijing than in Hamburg, which benefits from a temperate climate and the influences from the river Elba, and from both the North Sea and the Baltic Sea.

Table 2. Overview of sampled cities and UHI-related characteristics, in alphabetical order.

City, Country, No of Inhabitants, Total Area	Koeppen-Geiger Classification	Examples of Areas Affected by the Urban Heat Islands Problem	Green Space (% of Total Area)	Examples of Available Green Resources	Data Source:
Beijing , China 21.7 m 16,808 km ²	Dwa	Dongcheng district	46.2%	Jingshan Park	[122]
Belgrade city territory, Serbia, 1.7 mio., 3234 km ²	Cfa	City Municipality Vračar, Vračarski plato	1.8%	Karadordev park, Svetosavski plato	[123,124]
Autonomous City of Buenos Aires , Argentina, 3.072 mio., 203 km ²	Cfa	Retiro, Recoleta, Villa Soldati, Villa Riachuelo and La Boca	9.65%	Costanera Sur Ecological Reserve, Palermo Forest, Pres. Sarmiento Park, Indoamerican Park.	[125,126]
Dhaka , Bangladesh, 8.9 mio., 306 km ² ; Greater D. region 18 mio., 2161.17 km ²	Aw	Commercial district	14.5%	Gulshan Lake Park	[127]
Lagos , Nigeria, 21 mio., 1.171 km ²	Aw	City Hall, Yaba, Ikeja, Mushin, Ejigbo	5%	Tinubu Square Broad Street, Johnson Jakande (JJK) Park, Lekki Conservation Centre, Lakowe Lakes and Golf Resort	[79,128,129]
Hamburg , Germany, 1.7 mio., 755 km ²	Dfb	Hafen City, Hamburg Altona	44.1%	City Parks, District parks, Nature Reserves, e.g., Heuckenlock	[130,131]
Kuala Lumpur , Malaysia 1.58 mio., 243 km ²	Af	Kuala Lumpur city	30%	Bukit Nanas, Bukit Sungai Putih, Bukit Sungai Besi, Templer Park and Sir Gerald Templer	[132]
Montevideo Urban Area, 1 Mio, 231 km ² ; Metro-politan Area (AMM), Uruguay, 1.6 Mio., 1.641 km ²	Cfa	Ciudad Vieja, Centro, Aguada, Cordon	>10% (Urban) 25–30% (AMM)	Battle Park, Golf Park, Prado Park, Rivera Park, Rodó Park, Rambla Waterfront, Villa Biarritz	https://www.inumet.gub.uy/clima/estadisticas-climatologicas/tablas-estadisticas and http://sig.montevideo.gub.uy/
New Delhi , India 21.7 mio., 42.7 km ²	Cwa	Central Delhi and northern area	20.6%	Deer Park	[133]
Novi Sad , Serbia, 0.3 mio., 129 km ²	Cfb	Stari Grad, Grbavica and Nova Detelinara districts	7.6% (5% downtown; 15% outskirts)	Kamenički Park, Futoški Park, Limanski Park, Dunavski Park	[134,135]
Rio de Janeiro , Brazil 6.32 mio., 1.255 km ²	Aw, bordering on Am	Northern Zone	28,3%	Tijuca Forest, Flamengo Park	[116]
Seoul , Korea 9.8 mio., 605 km ²	Dwa	Commercial district	27.8%	Seoul Park, Tapgol Park	Seoul Metropolitan Government (2016; http://english.seoul.go.kr/2016-may-special-issue-2/)
Greater Sydney , Australia 5.64 mio., 12,367 km ²	Cfa	Penrith area	46%	Sydney Park, Sydney Olympic Park	[136]
Warsaw , Poland 1.73 mio, 516.9 km ²	Dfb	Central Śródmieście area	44.2%	Łazienki Park	[137]

Source: authors with a compilation of information from respective national agencies and further sources.

The data collected also serves to illustrate three main trends:

Trend 1—UHI affects all cities in an uneven way

The scope and impacts of UHI are not uniform: UHI affects the assessed cities and their inhabitants in different ways, i.e., depending on peculiarities of urban morphologies, and poses very different challenges linked to their peculiar microclimate. This, in turn, can amplify existing heat stress, going over and above higher baseline temperatures.

Trend 2—No city can be regarded as not being influenced by UHI

Whereas it is known that those cities located in the tropical climate zones—e.g., Kuala Lumpur with a tropical rainforest climate, Dhaka with a tropical wet and dry climate, and Rio de Janeiro with tropical monsoon climate—have to cope all year long with monthly average temperatures of already above 18 °C, it can also be seen that cities situated in temperate climates are equally affected. Here, it is seen that cities such as Montevideo, Belgrade or Buenos Aires, with a humid subtropical climate and monsoon-influenced humid subtropical climate, already show for at least one month an average temperature above 22 °C. Finally, those cities located in warm or hot summer humid continental climates—e.g., Hamburg, Warsaw and Beijing—with at least four months averaging more than 10 °C, also experience UHI.

Trend 3—Temperature discomfort and extreme heat are two separate issues

Data from the sampled cities show that even though UHI is a widespread phenomenon in all investigated cities, only two of the studied areas were attributed with and have suffered from extreme heat events—with a significant death toll—over the last ten years. They are both located in a humid subtropical climate zone: New Delhi and Greater Sydney; the former is a highly temperature sensitive city and the latter is located in a drought and heat-prone region. This suggests that whereas the media tend to mix the two issues, UHI needs to be differentiated from extreme heat periods.

However, even though the potential urban heat islands tend to occur mostly in central and commercial districts and downtown areas affluent in buildings, i.e., areas which presumably have less green areas and wind than average and a high number of exposed people, Wu et al., [138] have also documented seasonal UHI effects for a Chinese coastal city [138].

The vast differences in the share of green urban areas, ranging from 1.8% in Belgrade and 5% in Lagos to 46% in the Greater Sydney area and more than 46% in Beijing, suggest that these cities are already being exposed to UHI effects at different levels, a trend also described by Gunawardena et al. [76]. As the percentage of green areas can be assumed as a proxy of heat sensitivity and of natural resilience to heat stress, actions leading to increases in vegetated and blue areas may foster adaptive capacity and reduce exposure to heat island-related thermal distress, especially during heat waves.

Although their beneficial effect on thermal comfort has been long recognized, and there is a growing acknowledgement about its importance as an adaptation and resilience tool [139], current urban expansion processes tend to continue to deplete urban green resources [140]. This trend may be exacerbated in developing countries, where urbanization rates are already high. Under existing climate change scenarios, current green areas are thus expected to fall short of keeping outdoor thermal comfort in cities within a copiable range [141,142], a trend which may cause great thermal discomfort and, *inter alia*, negatively influence their livability. Therefore, it may be necessary to increase the share of a city's green areas as much as possible to generate real improvements on urban wellbeing [141–143].

The fact that UHI impacts all sampled cities, to a greater or to a lesser extent despite a wide range in share of green spaces, suggests that addressing the UHI effect effectively remains a complex phenomenon that requires a comprehensive analysis of a variety of influencing parameters to be able to identify appropriate adaptation tools. However, the data gathered in this study suggest that green areas, which are favorable to mitigating the UHI effect, i.e., a certain baseline, can be observed in all sampled cities. The difference in results gathered also indicates that some city planning schemes—such as the green net of Hamburg that serves to connect parks, leisure areas and further green areas with each other—already pay more attention to the potentially beneficiary influence of green

resources. This may be so for a variety of reasons underscored by the literature, among which the following may be mentioned:

1. Green areas play, in general, a key role as adaptation tools and also in the process of building resilience of urban dwelling [141,144]. This is especially true in relation to the thermal regulation of urbanized areas to counteract the UHI effect, due to the interception of direct solar radiation and increased evapotranspiration [145]. This may decrease the radiant temperature, profoundly influencing the thermal comfort (TC), usually measured as physiological equivalent temperature [146].
2. Tree covers are believed to have a useful effect on outside TC in cities [82,143,147]. Tree groves and forested parks have an average cooling effect of about 1 °C in air temperature [148], but could have a significant improvement on TC especially during heat waves [146,149]. However, denser tree canopies could have an adverse effect due to their increase of local humidity and reduction of wind speed that then results in a higher heat sensation [150,151]. The TC may be favored by shrub and grass cover in open areas or combined with trees [149,152], changing tree locations on artificial surfaces, e.g., parking lots or footways [153], integrating water bodies and irrigation systems [141,147,152,154] and also using green façades [143].
3. The positioning of the urban green resources can also strengthen the cooling effect, for instance, by placing trees or other green cover in more exposed street canyons or on façades [82,141,143,149,155], thereby increasing the green cover and the impervious surfaces ratio [156], as well as creating a well-distributed net of green spaces. Moreover, the size of the urban green resources matters: A recent study suggests that large urban parks with an area of at least 0.1 km² have the largest cooling effect in terms of cooling distance and intensity [72].

Figure 4 outlines some of the modalities of urban green spaces that may assist in reducing the impacts of the UHI effect.

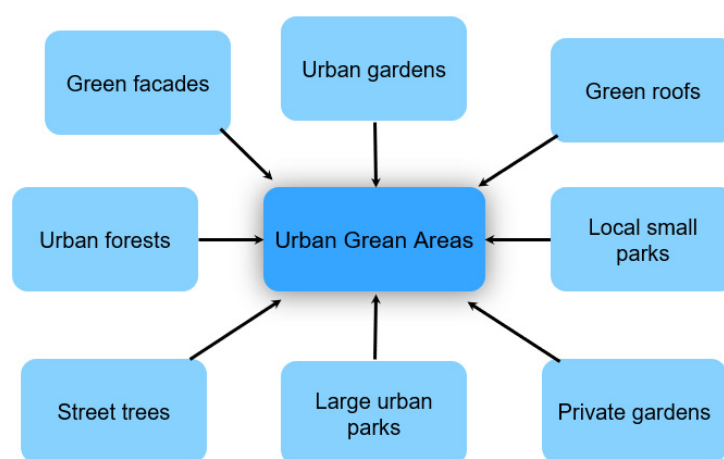


Figure 4. Some of the modalities of urban green spaces that may help to reduce UHI. Source: authors' own compilation.

The amount and distribution of urban green spaces is seen as a determinant of thermal comfort [82,141,157]. For instance, larger urban green areas (e.g., in Beijing, Seoul or the Sydney metropolitan sites) and the areas that immediately surround them tend to perform better [156,158–160].

Moreover, it is well known that keeping and increasing urban green resources leads to additional, multiple ecosystem services, such as improved water runoff and infiltration [141,144]. This is a fact seen in Hamburg, for instance. This trend will also have an essential impact on water availability for urban green areas, and consequently for evapotranspiration and cooling [76], while at the same time decreasing the risk of overflows [141]. Vegetation surface and gas exchanges also have a significant effect on controlling air pollutants by dry deposition and

absorption [161–164] and on noise reduction. The impact of green infrastructure is, however, highly context-dependent and could even lead to contrary effects. Hewitt et al. [165] proposed a framework and derived distinctive policy interventions to enhance the positive effects of the introduction of green resources. It may resemble a contribution to urban aesthetics and even criminality reduction [166], and it may also lead to improved biodiversity [167,168].

Despite the fact that opportunities for creating new green areas may be limited in cities, green spaces that are distributed evenly among cities may help to reduce vulnerability to UHI, since land cover, including green spaces and buildings, can influence both the social conditions and temperature levels [59,169,170]. This is currently being experienced in cities such as Dhaka, Lagos and Kuala Lumpur.

Moreover, solutions aimed at addressing or coping with UHI in a given city need to be adequate to its own topography. They also need to be commensurate with the socio-economic conditions they experience. Locally-based solutions also have the advantage of being able to motivate local communities to engage on mitigation efforts, instead of exclusively relying on planners.

6. Conclusions

As this paper has shown, urban heat islands can affect cities in different ways. Cities with a higher share of urban green areas seem more likely to be in a better position to cope with and adapt to the pressures posed by UHIs. By the same token, cities are more vulnerable to the UHI effect whenever the urban environment is densely built and green areas are not as prominent.

This paper has some limitations. For instance, the sample is limited to 14 cities across 13 countries only. In addition, the sample does not cover all climate zones. Also, it did not specifically look at the role played by extreme events, such as sweltering summers, nor focused exclusively on heat waves. These issues will be addressed in future papers. Despite its constraints, the novelty of the paper resides on the fact that it is a very extensive analysis of the literature with an empirical analysis of the data from across geographical regions, which is unprecedented in the literature. In addition, the work performed here does offer supporting evidence that shows that many cities are especially vulnerable to UHI, but not to the same extent, and it allows a rough profile to be built of the extent to which UHI affects them and their population.

The additional knowledge derived from this paper will be helpful to city authorities and planners, who often overlook the existence and future occurrence of UHI when developing city development plans.

Experiences from the sampled cities suggest that they should identify their areas of high exposure, assess the effects of countermeasures and predict future risks in view of increasing climate change and urbanization.

Given the potentially adverse effects of UHI on human health and wellbeing, further assessments to quantify the health risks of UHI, which are coupled with local vulnerability factors, are required. This is so for two main reasons: UHI is known to enhance the intensity and the duration of heat waves by retaining the high temperatures for longer periods of time. This situation can negatively influence human health, being particularly dangerous to the elderly and socially vulnerable people who cannot easily access shelter against the continuous heat. Also, when experienced over longer periods of time, UHI cannot only cause a general discomfort, but may also lead to respiratory difficulties, heat cramps, heat exhaustion, and, in extreme cases, heat stroke, especially among people suffering from existing health problems. These elements suggest that, apart from improved planning, citizens-driven initiatives are also needed, to put pressure on the relevant authorities, about the need to take more prompt action against UHI.

The implications of this paper are twofold. Firstly, it reiterates the complex interrelations of UHIs, heat waves and climate change. Secondly, it outlines the fact that keeping and increasing urban green resources leads to additional various benefits that may directly or indirectly reduce the impacts of UHI.

Concerning future prospects, it is important that city planners pay more attention to possible UHI effects when initiating new building projects or when adjusting current ones. In addition, a greater engagement of citizens is needed to encourage more prompt action and speed up the implementation of city plans. Moreover, since health issues are very relevant, it is important to pay due attention to the health hazards associated with UHIs, with a view toward protecting the most vulnerable people. Finally, existing green urban areas should be better maintained so that the valuable ecosystem services they provide will not be compromised in the longer term.

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